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# **TILT ROTOR AIRCRAFT AEROACOUSTICS**

## **Final Report**

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### **Summary of Research**

A fleet of civil tilt rotor transports offers a means of reducing airport congestion and point-to-point travel time. The speed, range, and fuel economy of these aircraft, along with their efficient use of vertiport area, make them good candidates for short-to-medium range civil transport. However, to be successfully integrated into the civilian community, the tilt rotor must be perceived as a quiet, safe, and economical mode of transportation that does not harm the environment. In particular, noise impact has been identified as a possible barrier to the civil tilt rotor. Along with rotor conversion-mode flight, and blade-vortex interaction noise during descent, hover mode is a noise problem for tilt rotor operations.

In the present research, tilt rotor hover aeroacoustics have been studied analytically, experimentally, and computationally. In the initial stages of the grant, overall analyses of tilt rotor noise problems were accomplished with Smith, Maisel, Brieger, Coffen, and Rutledge. Various papers on the subject were published as noted in the list of publications.

More recently, experimental measurements were made on a 1/12.5 scale model of the XV-15 in hover and analyses of this data and extrapolations to full scale were also carried out. A dimensional analysis showed that the model was a good aeroacoustic approximation to the full-scale aircraft, and scale factors were derived to extrapolate the model measurements to the full-scale XV-15. The experimental measurements included helium bubble flow visualization, silk tuft flow visualization, 2-component hot wire anemometry, 7-hole pressure probe measurements, vorticity measurements, and outdoor far field acoustic measurements. The hot wire measurements were used to estimate the turbulence statistics of the flow field into the rotors, such as length scales, velocity scales, dissipation, and turbulence intermittency. To date, these flow measurements are the only ones in existence for a hovering tilt rotor.

Several different configurations of the model were tested: (1) standard configurations (single isolated rotor, two rotors without the aircraft, standard tilt rotor configuration) (2) flow control devices (the "plate", the "diagonal fences") (3) basic configuration changes (increasing the rotor/rotor spacing, reducing the rotor plane/wing clearance, operating the rotors out of phase). Also, an approximation to Sikorsky's Variable Diameter Tilt Rotor (VDTR) configuration was tested, and some flow measurements were made on a semi-span configuration of the model.

Acoustic predictions were made using LOWSON.M, a Mathematica code based on Lowson's (1965) equation, and NASA Langley's WOPWOP (Brentner, 1986). For both codes, mean aerodynamic models were developed based on hover performance predictions from HOVER.FOR. This hover prediction code used blade element theory for the aerodynamics, and Prandtl's Vortex theory to model the wake, along with empirical formulas for the effects of Reynolds number, Mach number, and stall. Aerodynamic models were developed from 7-hole pressure probe measurements of the mean velocity into the model rotors.

LOWSON.M modeled a rotor blade as a single force and source/sink combination separated in the chordwise direction, at an effective blade radius. Spanwise, Mach-weighted integrals were used to find the equivalent forces and equivalent source strengths. LOWSON.M predictions were valid in the far field at low frequencies: approximately the first 10 harmonics of the full-scale blade passing frequency. However, WOPWOP could compute higher frequencies because it could model non-compact acoustic sources. To be consistent with this formulation, chordwise-accurate pressure distributions were used for WOPWOP input. These pressure distributions were computed in advance using EXJOUK.M, a Mathematica code which computed the pressure distributions of extended Joukowski airfoils using conformal transformations. The extended Joukowski airfoil sections were chosen to match the rotor blade cross sections as closely as possible.

Conclusions from the different phases of this research are listed below.

(1) The fountain flow was observed to be unsteady and intermittent, and shifted from side to side across the longitudinal symmetry plane of the model, as observed previously by Coffen (1992). Remnants of rotor tip vortices were carried by the mean flow back up between the rotor blades. The collision and upward turning of the fountain flow occurred over a stagnation region rather than a stagnation line, that extends approximately  $\pm 0.6$  m on either side of the longitudinal axis of the full-scale XV-15. The intermittency of the fountain flow was estimated by dissipation measurements.

A strong rotor/rotor interaction changed blade loading in the region where the two rotors were closest together, whether or not the aircraft was present, and caused an impulsive noise source preferentially radiated behind the aircraft. With the aircraft present, 7-hole pressure probe measurements showed a characteristic azimuthal variation in blade loading: it was first reduced, then increased abruptly, then reduced again as the rotor blade swept over the main wings from the leading edge to the trailing edge. Acoustic predictions from LOWSON.M using this characteristic blade loading showed good agreement with full-scale experimental data. This result is quite different than the earlier "velocity deficit model" (Coffen and George(1990), Rutledge et al. (1991)), which assumed that blade loading *increased* in the same region. However, the velocity deficit model is not consistent with other experiments such as Felker and Light (1988), and Mosher and Light (1994).

Turbulence measurements from the model showed three different regions in the flow field: (1) an anisotropic, large length scale, low velocity scale, low dissipation region corresponding to ambient turbulence ingestion (2) an intermittent region, whose turbulence statistics depended on the fraction of time that the fountain flow was present (3) an approximately isotropic, small length scale, large velocity scale, very high dissipation region corresponding to fountain flow turbulence ingestion. Three turbulence length scales were identified: an ambient turbulence scale,  $L = 1.6R$ , a fountain turbulence scale,  $L = 0.4R = h$ , and a length scale corresponding to remnants of tip vortices,  $L = 0.016R$ , where  $R$  is the rotor radius. The fountain turbulence seemed to obtain its length scale from the rotor disk-to-wing clearance,  $h$ . The numerous length scales and intermittency of the flow caused the measured turbulence spectra to show non-classical features. For example, the inflow of energy into the turbulence at the length scale of the tip vortex remnants caused a slower decay of energy with wave number than predicted by the Kolmogorov spectrum model:  $(kL)^{-5/3}$ .

(2) A flow control device called the "plate" blocked the fountain flow, and significantly reduced the transport of turbulence back into the rotor plane. A more practical device, the "diagonal fences", reduced the turbulence intensity in the fountain region by a factor of about 3, and reduced noise by 4 equivalent full-scale dBA behind the aircraft. The fences were believed to be successful because the tip vortices were trapped on the hub side of the fences, and could not be recirculated by the mean flow. The diagonal fences removed the well-known acoustic directionality of hovering tilt rotors, since the radiated noise was the same behind the model as it was in front of the model.

(3) Operating the rotors out-of-phase reduced the unweighted OASPL behind the aircraft, but had little effect after A-weighting. Cancellation occurred at the fundamental blade passing frequency only, which was not significant after the A-weighting. Even if perfect cancellation did occur, a LOWSON.M acoustic prediction showed that operating the rotors out-of-phase merely changes the far field directivity by reversing the lobes of maximum and minimum OASPL.

Moving the rotor plane closer to the wings reduces broadband noise radiation behind the aircraft. This was believed to occur because there was insufficient space for a well-defined wake with distinct tip vorticity. At the normal XV-15 rotor plane/wing spacing of  $h/R = 0.386$ , the turbulence obtained its length scale from  $h$ :  $L = h$ , whereas at half the rotor plane/wing spacing,  $h/R = 0.193$ , it would seem that a well-defined wake was not formed. Thus, the present research has identified rotor plane/wing clearance as a significant parameter in rotor broadband noise, which could be an important factor in future tilt rotor designs.

(4) With the VDTR rotors, the fountain flow was smaller, and less intermittent than the standard rotors, but had higher turbulence intensities and larger broadband acoustic sources right at the rotor tip in the fountain flow region. Remnants of the tip vortices remained in the proximity of the rotor tips, whereas they were carried further towards the hub by the fountain flow for the standard tilt rotor configuration. Broadband noise was about 4 dB higher for full-scale frequencies between 400 to 1000 Hz with the VDTR rotors.

Broadband noise was reduced for the VDTR when the rotor spacing,  $S$ , was increased, and when the rotor plane/wing clearance,  $h$ , was reduced.

For the VDTR, the rotor/rotor interaction was larger than for the standard tilt rotor. Acoustically, this interaction caused larger impulsive spikes in the wave forms measured behind the aircraft. The rotor/rotor interaction was reduced when the rotor spacing,  $S$ , was increased. Thus, moving the rotors farther apart reduces both broadband and rotor/rotor interaction noise, while moving the rotor plane closer to the wing reduces broadband noise.

In general, the VDTR was marginally worse acoustically behind the aircraft, and a few dB quieter in front of the aircraft. Although both discrete and broadband loading noise sources were larger for the VDTR, as discussed above, these were partially balanced by the lower disk loading and lower blade passing frequency.

(5) With semi-span models, the kinetic energy of the turbulence is zero at the image plane, and the large scale shifting of the fountain flow is absent. The fountain flow is higher on semi-span models:  $0.9R$  vs.  $0.5R$ , and it is recirculated further towards the hub:  $0.35 < r/R < 1.0$  vs.  $0.67 < r/R < 1.0$ . Also, the image plane changed the induced velocity

field into the rotors, and caused a high-velocity wall jet next to the image plane. This jet was probably caused by the perfect correlation between the tip vortex remnants and their "image vortices", which was absent on the full-span model.

Higher turbulence levels were measured in the inflow of the semi-span model at the stations near the hub. These higher turbulence levels were probably caused by the boundary-layer formed by the wall jet at the image plane, which contributed significant vorticity production to the fountain flow.

On the side away from the fountain flow, the rotor wake showed the expected contraction, and was correlated well by the prescribed wake of Kocurek and Tangler (1977). On the image plane side, the wake initially contracted, then expanded, and remnants of the tip vorticity were convected by the mean flow back up between the rotor and image plane, where they were rapidly diffused, stopped following repeatable paths, and their energy was cascaded into the turbulence of the fountain flow.

In general, semi-span models are a good approximation to hovering tilt rotors with respect to overall rotor performance, and wing download. Broadband rotor noise is over-estimated by semi-span models. For detailed flow information, development of turbulence models, and especially CFD code validation, flow measurements should be taken from full-span models.

The present research has led to better understanding and predictive abilities for tilt rotor hover noise. Complementary flow and acoustic measurements were made, suitable for CFD and aeroacoustic code validation, which are the only measurements of this kind in existence. Some noise reduction strategies and basic configuration changes were also investigated. It is hoped that this work will contribute to the development of the civil tilt rotor.

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